Nanometer-scale Science and Technology
Room: 311 - Session NS+NC-WeA

Nanoscale Devices and Sensors
Moderator: S. Evoy, University of Alberta, Canada

1:40pm **NS+NC-WeA1 CNTFET: Carbon Nanotube Power Transistors**, ***B. Lim***, *B. Hunt, E. Wong, M. Bronikowski, S. Jung*, Atomate Corporation **INVITED**

The carbon nanotube field effect transistor [CNTFET] has the potential to deliver functional performance and efficiency that exceed silicon-based power devices by more than an order of magnitude. The high carrier mobility, high power density, high thermal conductivity, and low on-state resistance of the semiconducting single-walled carbon nanotube can result in a significantly smaller device that operates much cooler and consumes less power. Furthermore, new applications not possible with silicon MOSFET devices can be enabled because of unique characteristics of the CNTFET architecture. This talk will cover the innovative architecture of an early proof-of-concept CNTFET developed by Atomate and some of the challenges to commercial success and acceptance.

2:20pm **NS+NC-WeA3 Transition Between Particle Nature and Wave Nature of Hole in Single-Walled Carbon Nanotube Transistor by Gate Voltage**, ***K. Matsumoto***, Osaka University, Japan

We have succeeded in fabricating the convertible transistor which can operate as a resonant tunneling transistor (RTT) and also as a single hole transistor (SHT) using single-walled carbon nanotube (SWNT) by modulating the strength of the coupling between the electrode and the quantum island using the gate voltage that changes the thickness of Schottky barrier, in which RTT is the device using wave nature of hole and SHT is the device using particle nature of hole. The sample has a SWNT contacted to the source and the drain electrode by Ti metal. The distance between both electrodes is 73 nm. The gate electrode is in the back side of Si substrate. Contour plot of differential conductance characteristic as a function of gate voltage and drain voltage at 7.3 K is measured. When the gate voltage VG is relative low at around VG =-10 V to -15, the plot clearly shows the Coulomb diamond characteristic. This means the device shows the particle nature of hole. Additionally, line shape quantum levels are appeared at both sides of Coulomb diamonds. The Coulomb diamonds are getting blurred with negatively increasing gate voltage around VG=-15 V to -20 V. The quantum levels are, however, still remaining. Finally, at relative high gate voltage at VG=-20 V to -25 V, Coulomb blockade is lifted and Coulomb diamonds are disappeared. However, quantum levels are still remaining, and current oscillate owing to the resonant tunneling through quantum levels. Thus, only by modulating the gate bias, the device shows the Coulomb blockade phenomena, that means the particle nature of hoe at low gate bias, and also shows the coherent oscillation of hole that means the wave nature of hoe at negatively high gate bias.

2:40pm **NS+NC-WeA4 Charge Transport in SWCNT Transparent Contacts**, ***T.M. Barnes***, *J.L. Blackburn, R.C. Tenent, M.J. Heben, T.J. Coutts*, National Renewable Energy Laboratory

Single-wall carbon nanotube (SWCNT) networks exhibit high electrical conductivity and optical transparency, allowing their use as transparent electrical contacts in photovoltaics and other opto-electronic devices. They are particularly well suited to applications requiring a contact that is flexible, hole-conducting, or solution processible. We have shown in previous work that these materials function well as transparent contacts in a variety of organic and inorganic photovoltaic devices. However, their opto-electronic performance still lags that of the best transparent conducting oxides. Improving charge transport through the networks should enable higher conductivity and the use of thinner (and more transparent) networks. In this work, we focus on the conductivity mechanisms of transparent SWCNT networks as a function of the ratio of metallic to semiconducting tubes and chemical doping. Conductivity in SWCNT networks is influenced by a variety of factors. Junctions between the semiconducting and metallic tubes are thought to strongly affect network conductivity, but this is not well understood. Following the method of Arnold,[1] we have produced films that contain a range of tube conductivity types varying from strongly semiconductor enriched (96%) to strongly enriched in metallic tubes (96%) to study the effect of tube-type polydispersity on transport. Temperature dependant resistivity measurements are combined with spectrophotometry to characterize the networks revealing that both intentional and unintentional doping has a strong effect on network conductivity, regardless of tube-type. Tube-type and tube quality do appear to affect the high temperature stability of the conductivity. We present a model effectively describing the conductivity mechanism at low temperature and explore the factors controlling conductivity at higher temperatures.

[1] Arnold, M. S.; Green, A. A.; Hulvat, J. F.; Stupp, S. I.; Hersam, M. C., Sorting carbon nanotubes by electronic structure using density differentiation. Nature Nanotechnology 2006, 1, 60-65.

3:00pm **NS+NC-WeA5 A Single-Walled Carbon Nanotube Thermal Sensor Integrated with CMOS Circuitry**, ***M.R. Dokmeci***, Northeastern University, *S. Sonkusale*, Tufts University, *C.-L. Chen*, Northeastern University, *V. Agarwal*, Tufts University

In this paper we present Single-Walled Carbon Nanotube (SWNT) thermal sensor integrated with CMOS integrated circuits. The chip was fabricated using the AMI 0.5um CMOS Technology. Electrical measurements from the assembled SWNTs yield ohmic behavior with a two-terminal resistance of ~44KOhms. The SWNTs were incorporated on to the CMOS chip as a feedback element of a two-stage Miller compensated high gain operational amplifier. The measured small signal ac gain (~1.95) from the inverting amplifier confirmed the successful integration of carbon nanotubes with the CMOS circuitry. After assembly, the thermal behavior of the CNT-CMOS system yield a TCR value of -0.33 measured through the operational amplifier indicating that the SWNT device has potential applications in temperature sensing. This paper lays the foundation for the realization of next generation integrated nanosystems with CMOS integrated circuits. Recently, numerous approaches for the synthesis and device applications of nanoscale materials such as nanotubes and nanowires are being demonstrated. Despite the exciting preliminary success of nanowire research, one of the limitations is the absence of integration of the nanostructures with CMOS circuitry. The heterogeneous integration of nanostructures with readout electronics not only improves the signal to noise ratio, but also provides a means to record, buffer and amplify the measured signals on the same chip leading to highly sensitive nanostructure based nanosystems. The nanotube-CMOS assembly (based on Dielectrophoresis) utilized electrodes realized from the metal 3 layer of CMOS process and did not require any extra processing steps. SEM imaging results and the I-V measurements both confirm the controlled placement of nanotubes on to the electrodes attached to the CMOS circuitry. The measured ac gain of the operational amplifier (~1.95) matched the calculations well (2). SWNTs have a significant thermal response. The measured gain from the op-amp at 100ºC was ~1.26 which corresponded to a decrease in SWNT resistance. In summary, we have demonstrated a technology for integrating carbon nanotubes on to functional CMOS circuitry. The technique is simple, versatile and high yield with potential applications for the realization of nanotube based bio and chemical sensors fabricated on CMOS electronics.

4:00pm **NS+NC-WeA8 Coherence and Polarization Properties of Thermal Radiation Emitted by Metallic Nanowires**, ***L.J. Klein***, IBM TJ Watson Research Center, *Y.Y. Au, S. Ingvarsson*, University of Iceland, *H.F. Hamann*, IBM TJ Watson Research Center

We investigate the coherence properties of the thermal radiation emitted from resistively heated individual metallic nanowires. High aspect ratio nanowires are fabricated by e-beam lithography with widths from 60 nm up to 2 µm, dimensions well below the wavelength of the emitted thermal radiation. The coherence of thermal radiation is probed by self interfering the radiation from the nanowire with its image in a movable mirror. As the mirror approaches the nanowire, well defined interference fringes are observed. From the fringe visibility we extract the coherence length of the emitted thermal radiation. For nanowire width above 2 um the coherence length of the thermal radiation emitted by nanowires is similar to blackbody radiator. As the nanowire gets narrower an increased fringe visibility and higher coherence length is measured. A lower bound for the coherence length for thermal radiation is estimated to be 30 µm for very narrow metal nanowires well above 4 µm for the blackbody radiation.Furthermore the coherence length is increasing as the temperature of the nanowire is decreased. For very narrow nanowires the thermal radiation is polarized with very high extinction ratio. Either changing the width of the nanowire or the nanowire temperature the polarization can be rotated from a longitudinal to a tranversal direction to the long axis of the nanowire. Both the increased coherence and polarization of the thermal radiation can be related to correlation of the charge fluctuation and charge confinement in narrow structures. We discuss various approaches to further increase the coherence of the thermal radiation emitted by nanowires and their applications as sub-wavelength coherent infrared light sources.

4:20pm **NS+NC-WeA9 Microwave Conductance of Silicon Nanowires**, ***M. Lee**, C. Highstrete,* Sandia National Laboratories*, A.L. Vallett, S.M. Eichfeld, J.M. Redwing, T.S. Mayer*, The Pennsylvania State University

The electrodynamic response of semiconductor nanowires across radio- to microwave frequencies is of great interest to both nanomaterial physics and high-frequency device applications of nanowires. It is of particular interest to highlight differences between nanowire and bulk characteristics of the same nominal material. We present measurements of conductance spectra on undoped, p-type, and n-type silicon nanowire (SiNW) arrays from 0.1 to 50 GHz at temperatures between 4 K and 293 K. Highly crystalline SiNWs were synthesized by VLS growth, assembled into arrays numbering between 11 to >50,000 NWs on co-planar waveguides, and measured using microwave vector network analysis. The complex conductance of all doped SiNW arrays was found to increase with frequency f following a sub-linear power law f^s, with $0.3 \leq s \leq 0.4$, and to agree with the expected Kramers-Kronig relation between real and imaginary parts of the conductance. This frequency dependence was independent of the number of SiNWs, while the conductance magnitude roughly scaled with the the number of SiNWs in the arrays. Such a sub-linear frequency dependent conductance is inconsistent with conventional Drude conductivity seen in bulk doped silicon, but is consistent with behavior found universally in disordered systems, although with an unusually small value of s. The magnitude of the microwave conductance was also observed to be sensitive to exposure to air, with p-type SiNWs becoming more conductive and n-type becoming less conductive upon venting the vacuum test chamber to air. We speculate that probable cause of the inferred disorder arises from Si/SiO_x interface states dominating the conduction due to the high surface-to-volume ratio and cylindrical geometry of the nanowires. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. Work at Penn State was supported in part by NSF MRSEC: Center for Nanoscale Science Grant # DMR-0213623, and NSF NIRT Grant # ECCS-0609282.

4:40pm **NS+NC-WeA10 A Quantitative Single-Molecule Analysis of Thioether Rotors and Motors**, ***E.C.H. Sykes**, A.E. Baber, H.L. Tierney*, Tufts University

We have conducted a fundamental, single-molecule study of the motion of a set of thioethers supported on Au surfaces. These molecules constitute a simple, robust system with which to study molecular rotation as a function of temperature, applied field, and the proximity of neighboring molecules. Low-temperature scanning tunneling microscopy has allowed us to measure the rotational energetic barriers and pre-exponential factors of a set of thioethers. Our results reveal that ratcheting of the second carbon of the alkyl chain over the surface is responsible for the barrier. Through a series of controlled manipulation experiments we have switched the rotation on and off reversibly by altering either the electric field of the tip or by moving the molecules towards or away from one another. The thioether backbone constitutes an excellent test bed for studying the details of both thermally and electrically driven molecular rotation at the single-molecule level.

5:00pm **NS+NC-WeA11 Surface Modified Resonant Cantilevers for Specific Bacterial Detection**, ***A. Singh**,* University of Alberta, Canada*, N. Glass, L. Gervais, M. Gel,* National Institute for Nanotechnology NRC, Canada*, M. Tolba, L. Brovko, M. Griffiths,* University of Guelph, Canada*, S. Evoy*, National Institute for Nanotechnology NRC, Canada

Bacteriophages are class of viruses that infect bacteria and use them as a host for replication. These phages are highly bacterial-strain specific and thus have the potential to be used as naturally sensitive and selective probes for the detection of pathogens. We have already reported the use of the biotin-streptavidin affinity to immobilize biotinylated phages onto gold surfaces. However, the need of genetic modification limits the versatility of this approach. Thus, there is a need to develop a simple universal process to immobilize phages onto sensor surfaces. We studied different surface modification protocols for gold substrates and their efficiency to capture phages and subsequently the bacteria was analyzed by using SEM and Fluorescence Microscopy. Wild type T4 phage was chosen as the model system for the study with E. coli EC12 strain as the host bacteria. Control experiments were performed with 3 non-host bacterial strains (E. coli 6M1N1, NP 30 and NP 10) to ensure specificity and selectivity of the system. The thiol binding chemistry on gold surfaces was utilized to modify the surface by using cysteine and cysteamine. The results revealed that the gold surfaces modified with cysteine or cysteamine and further activated by treatment with gluteraldegyde enables best phages density and bacteria capture as compared to other modifications. The SEM study for phage immobilization shows that a surface density of 15 ± 3 phages/µm2 was obtained. In our previous work, the biotin-streptavidin interaction was used to immobilize biotin expressing genetically-engineered phages which gave us a surface density of 10 ± 5 phages/µm2. Thus, the surface modification of the substrate enables a better phage density. The protocol was then duplicated on to a gold-coated cantilever surface, which again showed successful phage immobilization and subsequent bacterial capture. Microcantilever-based detection has been shown to have a mass sensitivity equivalent to that of a single bacterium. The shift in the resonance peaks of the cantilever, before and after the treatment of phage immobilized surface to bacteria, has been used as a measure to confirm bacterial capture. Thus, we illustrate a universal approach towards specific capture and detection of pathogenic bacteria, which could be potentially be employed in numerous sensing platforms such as microresonators, surface plasmon resonance, and quartz-crystal microbalance.

5:20pm **NS+NC-WeA12 Scanning Probe/Scanning Electron Microscope for In-Situ Nanoscale Experiments Based on a Thermally-Actuated, Piezoresistive Cantilever Sensor under Dynamic Frequency Control**, ***D.F. Ogletree**,* Lawrence Berkeley National Laboratory*, Tzv. Ivanov, Y. Sarov, I.W. Rangelow*, Technical University of Ilmenau, Germany

A scanning probe microscope has been integrated into a variable-pressure scanning electron microscope for in-situ nanoscale experiments. The heart of the instrument is a self-sensing, self-actuated cantilever[1] oscillated at resonance for non-contact dynamic force or tapping mode imaging. We have employed piezoresistive readout and thermally driven bimorph actuation. The integrated Si tips have been formed at the end of the cantilever by a micro-machining process. A digitally-synthesized sine wave of variable frequency and amplitude excites the cantilever by driving an integrated resistor which generates thermal stress. Lever deflection is monitored by an integrated piezoresistive sensor, and the SEM is used to calibrate the sensor response. A commercial digital phase-lock loop controller[2] adjusts the drive signal to maintain a constant oscillation amplitude and fixed phase shift relative to the drive frequency. A lab-built piezo scanner including a lateral translation system and a commercial nanotranslator for the tip approach complete the system. The system performance and noise levels will be compared for operation at the first, second and third resonant modes of the cantilever sensor, and the effects of ambient gas pressure will be discussed.

[1]Ivo W. Rangelow, Microelectronic Engineering 83 (2006) 1449–1455.

[2]PLLpro, RHK Technology, Inc., Troy, Michigan, USA.

Authors Index

Bold page numbers indicate the presenter